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Carderock Division
West Bethesda, MD 20817-5700

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Technical Report

Investigation of a Roof Tube Failure From a Utility Boiler

by

David A. Shifler

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David A. Shifler

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Carderock Division
Naval Surface Warfare Center
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West Bethesda, MD 20817-5700

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A recent failure from the roof tube section of No. 3 Boiler at IHDNSWC, Indian Head, MD occurred. Evaluation of the tube failure indicated extremely heavy waterside deposits that had migrated from other areas of the boiler. These deposits led to local overheating and creep rupture on the hot crown of the roof tube. Waterside pitting accentuated the applied tube stresses and decreased the time to rupture. The boiler should be examined for other occurences of heavy boiler deposits. Affected roof tube sections should either be removed or the boiler chemically or mechanically cleaned.

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This work was performed by the Marine Corrosion Branch (Code 613) of the Naval Surface Warfare Center, Carderock Division for Naval Surface Warfare Center, Indian Head (David Boyle, Code 094CDB). The work was performed under work unit 1-613-215. Supervision during the course of this work was provided by Mr. R.J. Ferrara.

ABSTRACT

A recent failure from the roof tube section of No. 3 Boiler at Indian Head Division, Naval Surface Warfare Center (IHDNSWC), Indian Head, MD occurred. Evaluation of the tube failure indicated extremely heavy waterside deposits that had migrated from other areas of the boiler. These deposits led to local overheating and creep rupture on the hot side crown of the roof tube. Waterside pitting accentuated the applied tube stresses and decreased the time to rupture. The boiler should be examined for other occurrences of heavy boiler deposits. Affected roof tube sections should either be removed or the boiler chemically or mechanically cleaned.

BACKGROUND

A utility boiler recently experienced a tube failure in the roof section during a hydrostatic test at the Indian Head Division of the Naval Surface Warfare Center (IHNSWC) at Indian Head, MD. This Combustion Engineering (CE) boiler is reportedly operating at 825 psig since 1955. This failure occurred in sample was from one of three utility boilers at IHNSWC that supplies power to the base. One boiler is operated continuously for a one-year period in alternating years, while maintenance is achieved on the other boiler. A sample from the failed tube was submitted to CDNSWC Corrosion Branch (Code 613) for examination and determination of the cause of failure.

EXAMINATION

The failed roof tube sample was removed and found to contain a heavy waterside deposit on the hot side of the tube. Subsequent examination of other neighboring roof tubes in the vicinity of the rupture revealed the lack of heavy waterside deposits in corresponding areas. Previous analysis of boiler deposit in this area indicated that the deposit contained a high (~ 80 wt. %) copper/copper oxide content, although utility boiler components are, at present, reported to be of all ferrous materials. Boiler water also has been tested at intake ands discharge and found to contain less than 1 ppm copper.

Figure 1 shows that the tube failure consisted of a one-inch longitudinal split along the hot side. This split coincided with local bulging of the tube at the hot side crown. The tube sample was cut along the longitudinal, membrane axis. Figure 2 shows that heavy deposits exist around the failure along the hot portion of the tube. A moderate amount of waterside deposition had occurred along the tube membranes; deposits were lowest along the cold portion (back side away from the flame). A side view of the respective waterside deposits (Figure 3) indicated that the hot deposit was one-inch thick in some places along the sample. The cold side deposit was approximately 0.020 inch thick near the tube membrane, while the deposit along the center of the cold side were less than 0.005 inch thick.

Deposits were mechanically removed by scraping with a hard tool and by vibrating with a small oscillating engraving pen in accordance with Test method A (mechanical removal) of ASTM 3483 [1]. The results are listed in Table 1. The hot side deposit totaled 1000.9 g/sq.ft. while the cold side deposit was 61.78 g/sq. ft.. The quantity of deposition found on the hot side is extremely unusual for a low pressure (825 psig) boiler.

The waterside deposit removed from the hot side by scraping and oscillatory procedures were combined and analyzed by Powell Labs Ltd. (Baltimore, MD) via atomic absorption and ion chromatography. The results listed in Table 2 indicate that the deposit contains high levels of copper oxide and copper metal amounting to 44 to 49 wt%. Magnetite, a normal oxidation product of boiler steels, constitutes about 36 wt.%.

Removal of the waterside deposit exposed the presence of random pitting. The nominal wall thickness for the 3.0-inch I.D. tube is about 0.221 inch. Pits on the cold side were 0.010 to 0.025 inch deep with the deeper pits located along the tube membrane (which is not unusual for boiler tubing). Pitting along the hot side was 0.027 to 0.055 inch deep. General thinning of the tube wall at the failure reduced the general wall thickness to about 0.121 to 150 inch. Pits around the failure region reduced the minimum wall to approximately 0.103 inch.

Specimens from the hot side and cold portions of the tube were selected for metallographic evaluation. The microstructure along the cold side (Figure 4) displayed a slightly banded configuration of ferrite and pearlite – a normal morphology of low carbon steel.

A magnified view of the cold side microstructure (180° and opposite from the failure) as shown in Figure 5 attests to the lamellar nature of the pearlite colonies in the ferrite matrix. Dark intragranular phases are observed and are likely composed of minor alloy constituents such as iron and manganese sulfides or silicates as well. The 0.004-0.006 inch thick waterside deposit, shown in Figure 6, along the cold side tended to porous. Some copper metal was located in the deposit.

The microstructure along the hot side crown of the tube, but about 4 inches from the failure (Figure 7), discloses a relatively dense waterside deposit 0.001-0.002 inch thick with a more porous layer 0.003-0.011 inch thick. Copper metal particles are interspersed in the more porous layer. The tube substrate displays a matrix of pearlite and ferrite that shows no signs of thermal degradation as confirmed by the magnified photomicrograph in Figure 8.

The waterside deposit in the vicinity of the failure exhibited several distinct layers of oxide (Figure 9). There was also heavy oxidation and corrosion of the waterside surface. The deposit shown in this photomicrograph is 0.024-0.028 inch thick. Some of the layers are quite dense while others are very porous. One layer exhibits a dispersion of copper metal particles while still another layer revealed needle-like, fibrous oxides. The thick, porous deposits of mainly iron oxides, copper oxides, and copper metal could have a relatively high insulating value that could provide opportunities where tube overheating could occur (Figure 10).

In Figure 11, the tube microstructure near the failure (~ 0.5 inch away) displayed complete spheroidization of the carbides from overheating. Voids developed at grain boundaries, particularly at three-grain junctions; these voids tend to be oriented perpendicular to the tube surface. The formation of these voids is due to long-term overheating and creep rupture. Some of the voids have grown and coalesced into larger voids and incipient microcracks; some of the largest voids have formed surface oxides. There is slight elongation of the grains as a result of tube swelling and expansion. The photomicrograph (Figure 12) shows a magnified view that clearly shows that the carbides at former pearlite colonies have fully spheroidized. Some of these carbides have dispersed into the grains. Other random carbides are present along the grain boundaries; , voids have formed at some of these grain

boundary sites. Void formation and propagation occurred in a direction perpendicular to the hoop stress.

Voids initially formed at three-point grain boundaries, grew, and coalesced to form larger voids and microcracks. A few of these microcracks grew in the areas of highest stress to form macrocracks. Formation of these macrocracks increased the local applied stress, causing the cracks to grow with time. Figure 13 shows the macrocrack that led to a through-wall failure. The fracture surface is covered with a heavy oxide scale which appears to indicate that crack propagation occurred over a relatively long time. Some copper from the waterside surface has become embedded in the oxide scale.

DISCUSSION

The waterside deposit was extremely heavy and unusual for a roof tube from a low-pressure boiler. The presence of high levels of copper in the tube deposit reportedly from the present, all-ferrous boiler system, and without any apparent contribution from the boiler water source, tends to suggest that the deposit had formed at a time when copper alloys tubes were incorporated as part of the condenser or feedwater heater. The presence of nickel in the deposit tends to suggest that a copper nickel alloy was used either in the condenser or the feedwater heater. The porosity and the presence of this heavy deposit only in this roof tube also tends to suggest that the deposit slowly migrated to this site from other boiler sites. Formation of a local galvanic cell between copper metal and the steel surface may cause pitting.

The presence of the heavy deposits on the roof tube sample interfered with normal heat transfer. The horizontal roof tubes in the upper portion of the boiler, such as found at Indian Head, are also prone to sluggish coolant flow. Both of these factors lead to increasing tube metal temperatures leading to creep rupture. The examination of the tube microstructure around the failure indicated a temperature of around 900 °F. Analysis of the tube deposit indicated that the roof tube steel was carbon steel since it contained neither chromium nor molybdenum. Creep strength is affected by a number of metallurgical factors such as grain size, microstructure, and chemical composition. Creep resistance is improved by adding alloying elements such as molybdenum, tungsten, or chromium to the carbon steel. The

present carbon steel tube could conform to ASME SA 192 or SA 210 chemical specifications. The oxidation limit and maximum allowable temperature for carbon steel is 850 °F. Temperatures exceeding this limit led to localized overheating and thermal degradation of the tube microstructure which led to a spheroidized carbide morphology that has a lower creep resistance.

Creep resistance is dependent on both temperature and stress. Higher temperatures and/or stresses lead to accelerated creep and shorter time to eventual rupture. In the present case, heavy deposits elevated tube metal temperatures to ever higher values which, in time, led to spheroidization and initial creep void formation. Swelling of the tube decreased the wall thickness and increased the applied tube stresses by the reduction of the tube cross-sectional area; this accelerated the rate of creep. Waterside pitting and oxidation caused further tube metal losses and increased the creep rate, thus decreasing the time to eventual creep rupture. These type of failures in boilers are in a number of publications [2-4].

MITIGATION AND CONTROL

Susceptible sections of the boiler where high heat transfer occurs should be evaluated for the presence of heavy deposits that could cause tube metal temperature to elevate to values that creep may be experienced during the normal life of the boiler. Tube sections with tube blistering or bulges should be further examined, and removed if necessary. If heavy deposits are found in sufficient areas and frequency within the boiler, chemical cleaning should be considered. The water treatment program should also be evaluated.

REFERENCES

1 - D-3483-83 (1994), "Standard Test Methods for Accumulated Deposition in a Steam Generator Tube", Annual Book of ASTM Standards, Conshohocken, PA, v. 11.02 (1994).

2 - H Thielsch, "Defects and Failures in Pressure Vessels and Piping", Reinhold, New York (1965).

3 - D.N. French, "Metallurgical Failures in Fossil Fired Boilers", 2nd ed., John Wiley & Sons, New York (1993).

4 - R.D. Port, H.M. Herro, "The Nalco Guide to Boiler Failure Analysis", McGraw-Hill, New York (1991).

Table 1. Deposit Loading (Deposit Density) Results from Failed IHNSWC Roof Tube

Tube Location	Removal Method	Deposit Mass (g)	Area of Removal (sq. in.)	Deposit Density g/sq. ft.
HOT SIDE	Scraped	106.396	18.09	846.9
	Oscillating	20.728	18.09	164.0
TOTAL				**1000.9**
COLD SIDE	Scraped	0.00	13.47	0
	Oscillating	5.779	13.47	61.78
TOTAL				**61.78**

Table 2. Report of Deposit Analysis
(Powell Labs Ltd. Baltimore, MD)

Constituents, As	**Percent by Weight**
Iron (Magnetic), Fe_3O_4	35.8
Iron (nonmagnetic), Fe_2O_3	NONE
Iron (Metallic), Fe	NONE
Copper (Metallic), Cu	8.5
Copper Oxide, CuO	40.1
Nickel, NiO	1.4
Zinc, ZnO	0.2
Chromium, Cr	TRACE
Molybdenum, Mo	NONE
Aluminum, Al_2O_3	0.2
Manganese, MnO	0.5
Calcium, CaO	0.7
Magnesium, MgO	0.4
Sodium, Na	1.8
Phosphate, P_2O_5	1.8
Sulfate, SO_3	0.1
Sulfide, S	NONE
Chloride, Cl	NONE
Carbonate, CO_2	NONE
Silica, SiO_2	9.7
Carbon, C	NONE
Organics	NONE
Loss of Ignition	1.7
Water of Hydration	PRESENT
* Copper Oxide expressed as Cu_2O	36.0

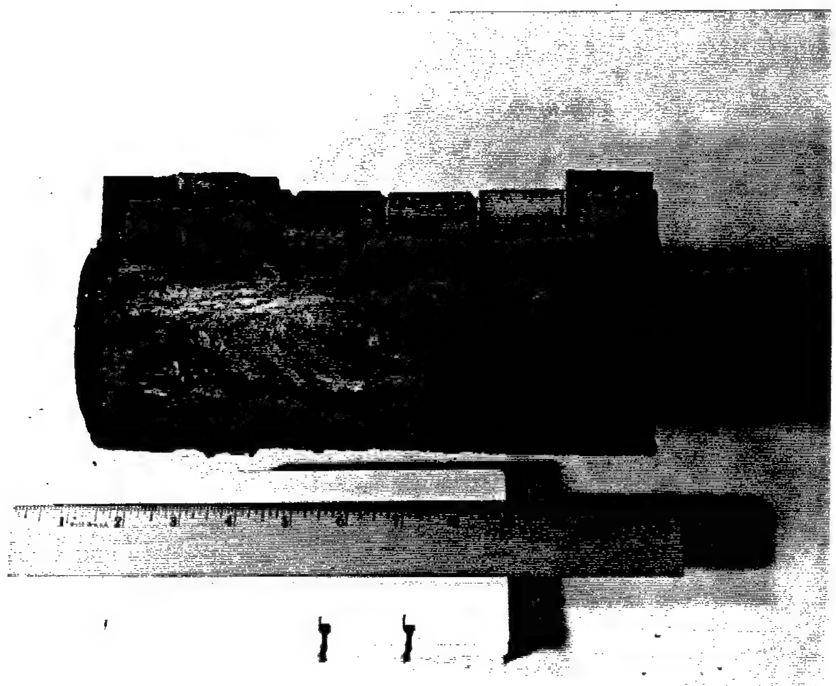

Figure 1 Roof tube "as received". Narrow one-inch long failure is along the hot side crown.

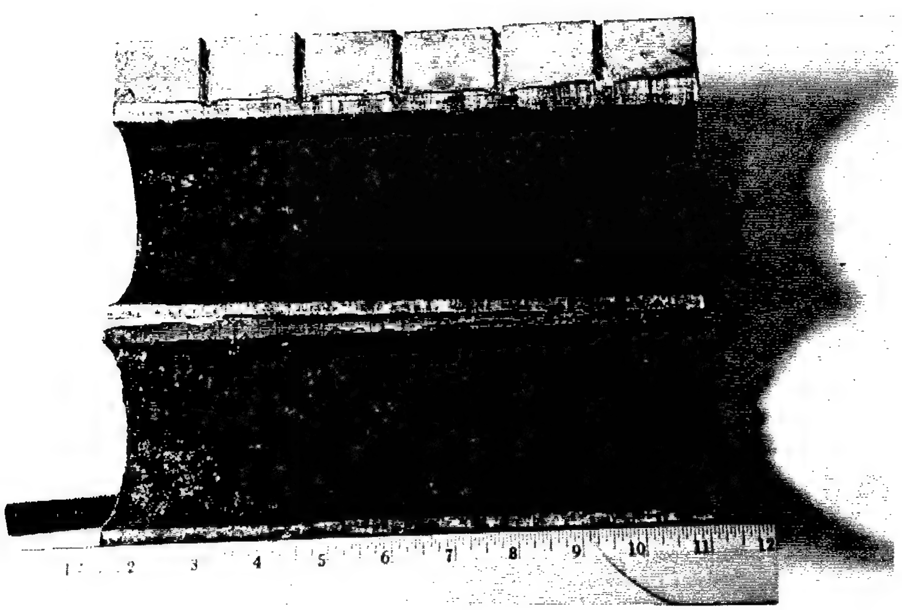

Figure 2 - Waterside surfaces of roof tube display heavy deposits on hot side (bottom tube half). Moderate deposits located at the tube membranes with lesser amount on the cold side.

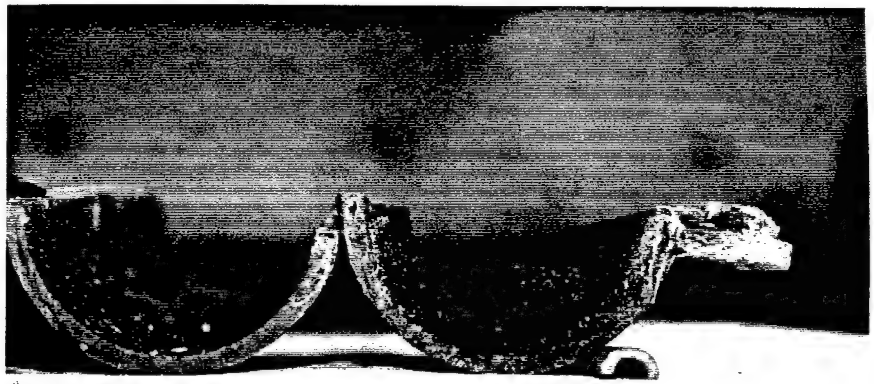

Figure 3 – Side view of tube sample reveals that hot side deposits are as much as 1.0 inch thick. Relatively little deposition was present on the cold side.

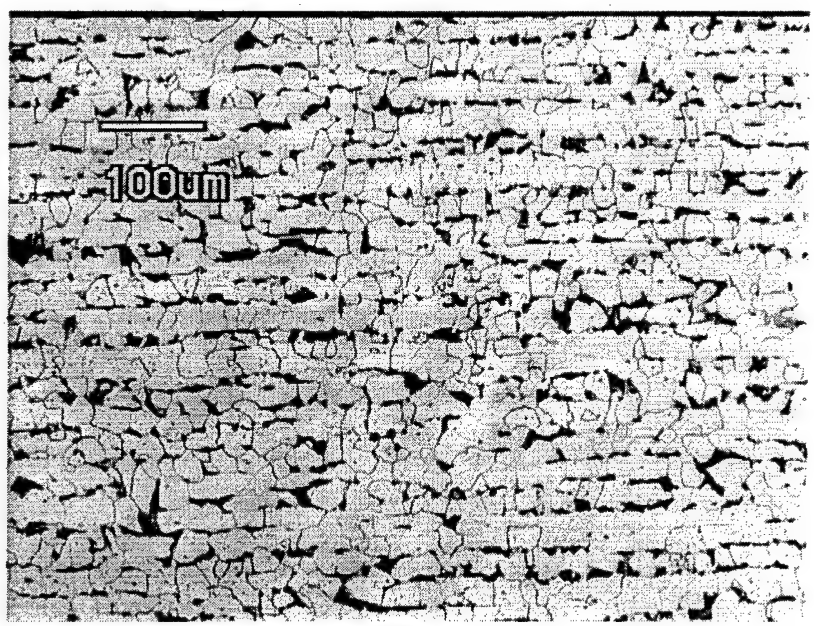

Figure 4 – Microstructure of the cold side displays a slightly banded ferrite morphology with pearlite. Magnification - 210X.

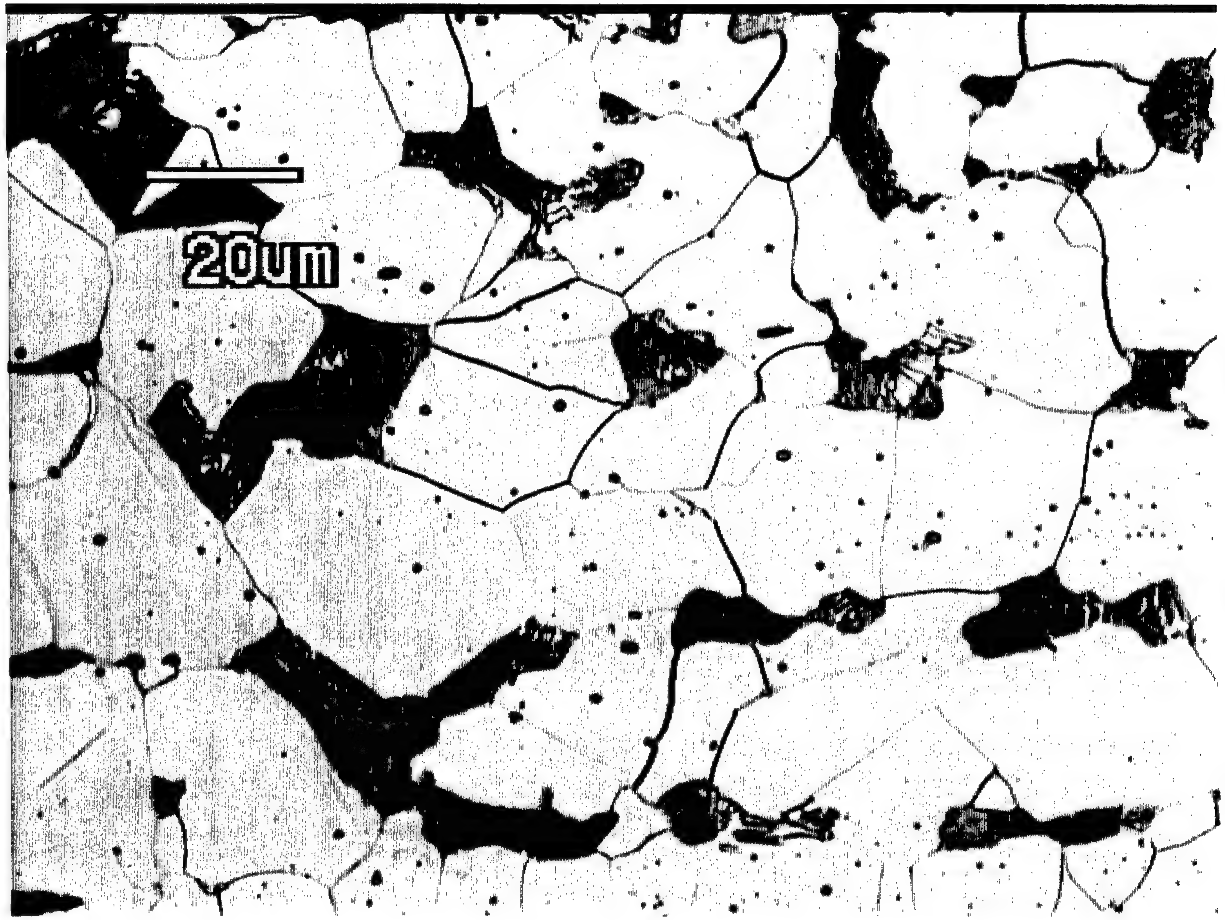

Figure 5 – Magnified view of Figure 4 microstructure shows the lamellar carbides in the pearlite colonies. Spherical phases are small alloy constituents such as oxide and sulfide inclusions. Magnification - 1050X.

Figure 6 – Cold side oxide scale is about 0.004-0.006 inch thick, but tends to be porous. Copper metal is mixed in the deposit. Magnification - 210X.

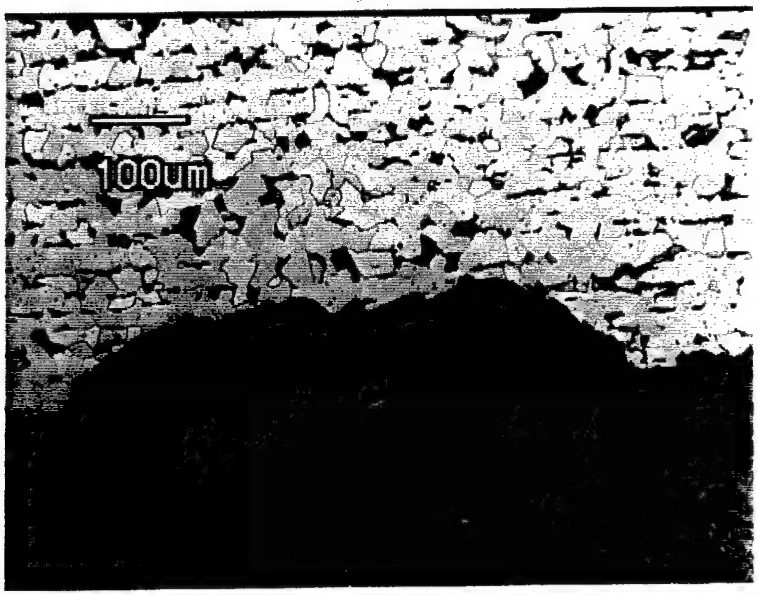

Figure 7 – Microstructure along hot side crown displays a thick waterside deposit with some mixing of copper metal particles. The underlying tube matrix has not been overheated. Magnification - 210X.

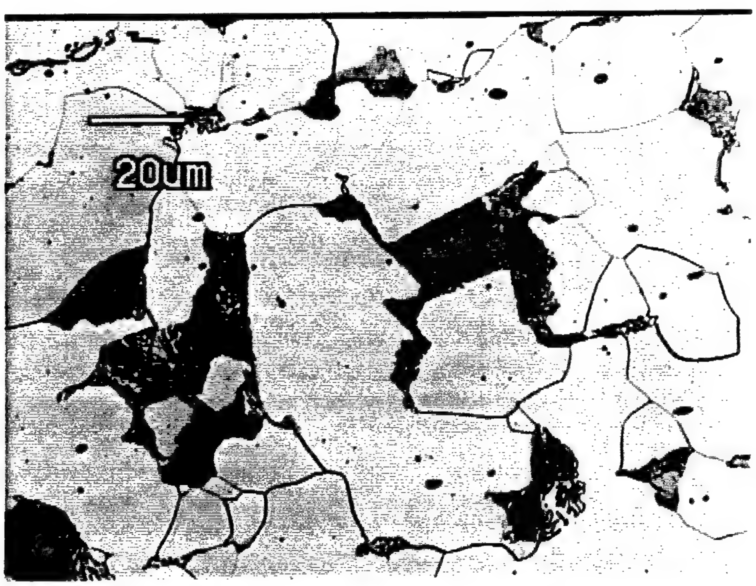

Figure 8 – Magnified view of Figure 7 shows no thermal degradation of the ferrite-pearlite tube matrix along the hot side area. Magnification - 1050X.

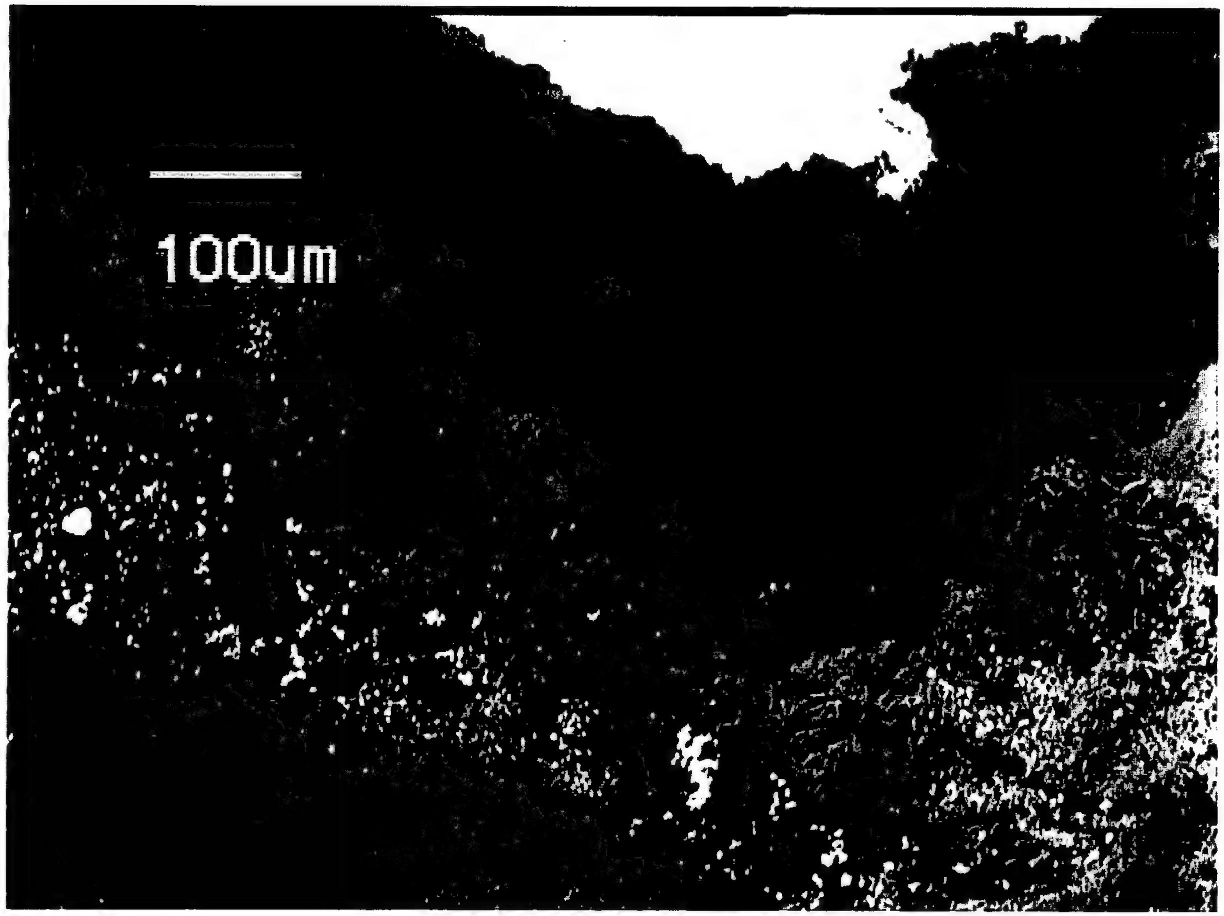

Figure 9 – Hot side deposit in the vicinity of the failure displays several layers and waterside oxidation/corrosion. Some layers are dense while others are very porous. One layer displayed needle-like, fibrous oxides. Another layer contains a number of particles of copper metal. Magnification - 210X.

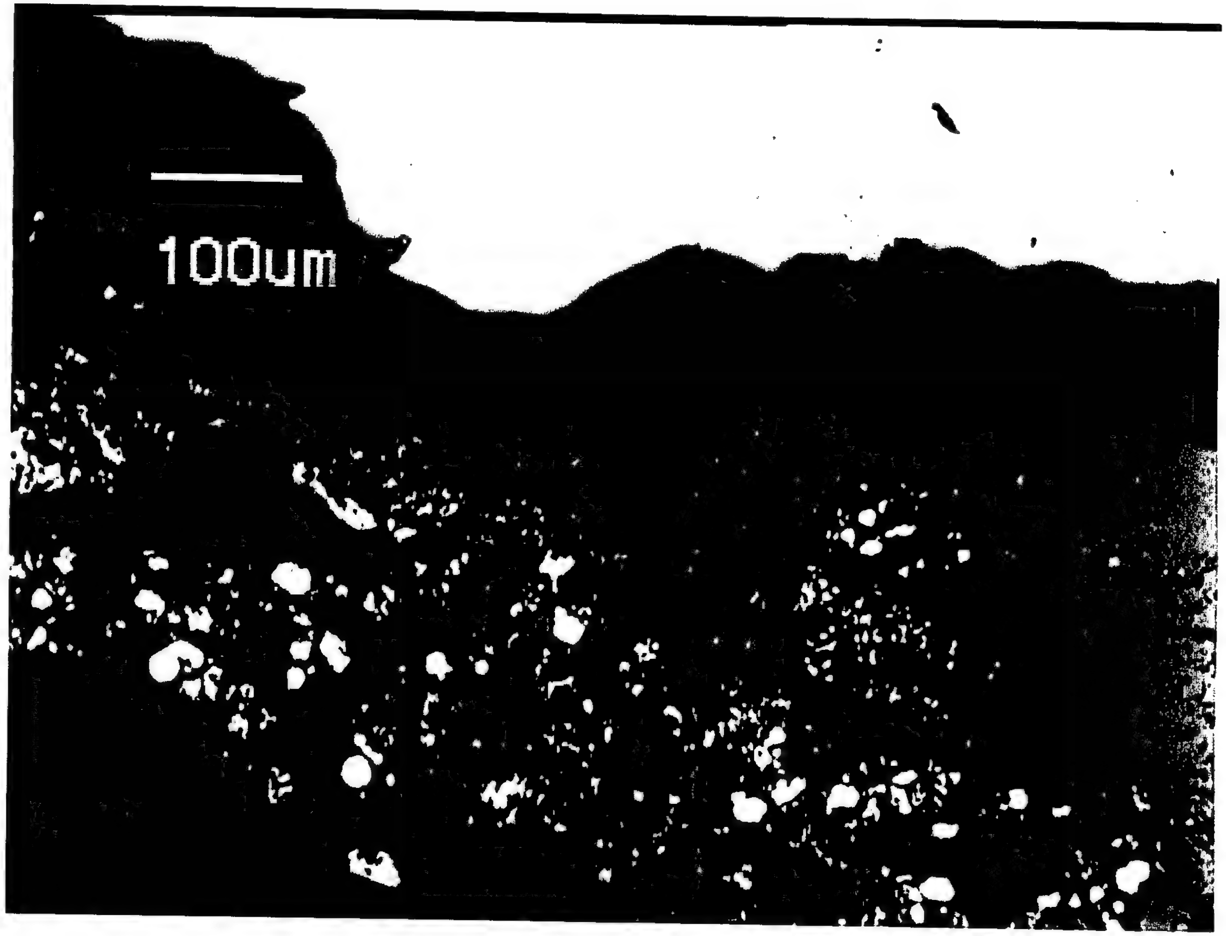

Figure 10 – Waterside deposit along hot side crown shows deposits containing mainly iron oxides, copper oxides, and copper metal. The high porosity of the thick deposit could provide opportunities for overheating. Magnification - 210X.

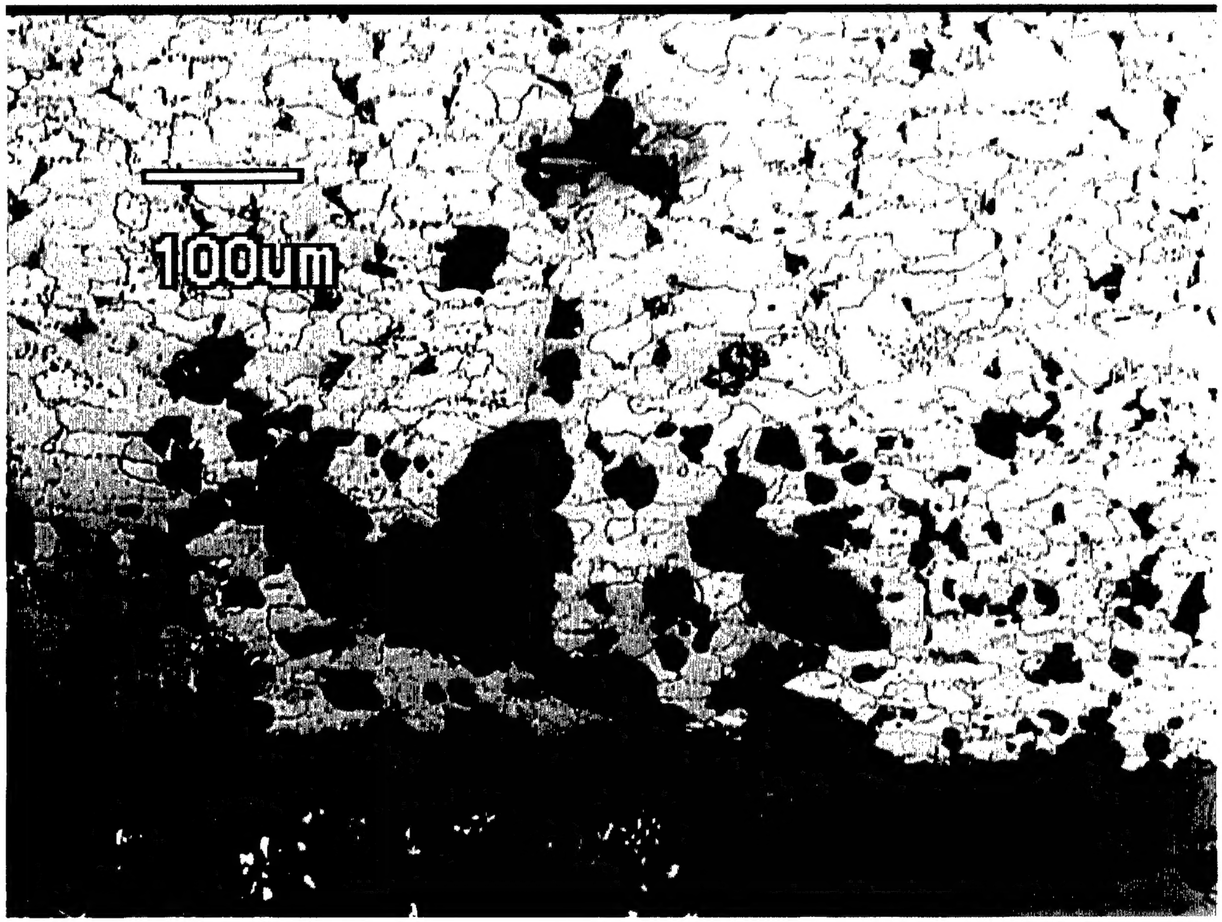

Figure 11 – Waterside surface, hot side, near failure. Carbides in prior pearlite colonies have completely spheroidized from overheating. Creep voids have developed at grain boundaries; some of these voids have grown and coalesced. Magnification - 210X.

Figure 12 – Carbides are fully spheroidized from thermal degradation near failure. Voids (dark sites) have formed along the grain boundaries that are perpendicular to the direction of applied stress. Magnification - 1050X.

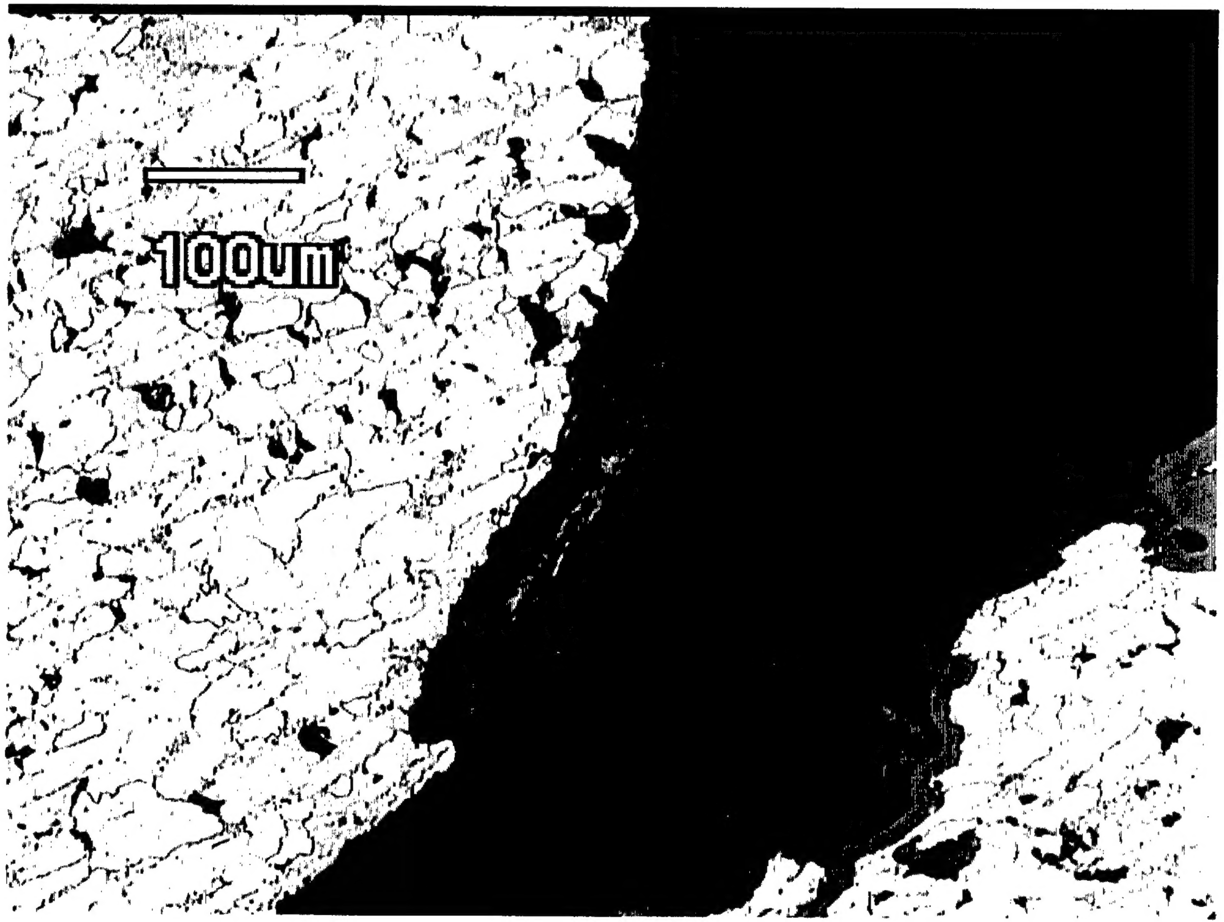

Figure 13 - Fracture surfaces near tube midwall. The fracture surfaces are covered with a heavy oxide scale. Copper metal has been transported to this site. Creep voids found in the tube matrix along the fracture. Magnification - 210X.

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